Research Article

Critical Period of Weed Control and Herbicide Performance in Quinoa (*Chenopodium Quinoa* Willd.)

Most. Nasrin Bari Neela, Tanvir Ahmad Sourav, Md. Hasanuzzaman and Sheikh Muhammad Masum*

Department of Agronomy, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh.

Abstract | Quinoa (*Chenopodium quinoa* Willd.) is a nutrient-rich crop with a rising global demand but faces production challenges in Bangladesh due to intense weed competition, making the identification of its critical period of weed control (CPWC) essential for minimizing yield losses. This study was conducted to determine the CPWC for quinoa and assess the efficacy of selected pre-and post-emergence herbicides on quinoa growth and yield. Laboratory and pot experiments assessed the phytotoxicity of pendimethalin, mesotrione + atrazine, acifluorfen + clodinafop propargyl at graded doses, while a field trial was arranged in an RCBD with 12 weed management treatments. Weed density, biomass, growth attributes, SPAD values, yield components, and seed yield were recorded. The results showed that pendimethalin at 2000 mL ha^{-1} effectively suppressed weeds without adverse effects on quinoa seed germination or negative effects on initial seedling growth, whereas the application of mixed herbicides caused phytotoxicity to the crop. Weed flora comprised 14 species, dominated by *Cynodon dactylon*, *Eleusine indica*, and *Cyperus rotundus*. The yield and yield contributing traits including SPAD value (46.17), effective branches plant^{-1} (19), inflorescences plant^{-1} (20), 1000-grain weight (3.49 g) and yield (2.36 t ha^{-1}) were found highest under weed-free conditions up to two weeks treatment compare to other weed control strategies. In contrast, season-long weed competition reduced yield by 65%. Results of logistic regression revealed that the critical period of weed control of quinoa field is 34-60 days after seed sowing.

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***Correspondence** | Sheikh Muhammad Masum, Department of Agronomy, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh; **Email:** smmasum607@sau.edu.bd
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Introduction

Quinoa (*Chenopodium quinoa* Willd.), which is native to South America's Andean region, is becoming increasingly popular due to its culinary versatility and health benefits (Repo-Carrasco *et al*., 2010). It was referred to as the "mother grain" by the Incas (Oustani *et al*., 2023). Though it was rejected as 'Indian food', it did not become extinct as it is tolerance to various stressors including drought, salinity, heat, cold, frost, heavy metals, and UV-B light irradiance. (Hinojosa *et al*., 2018; Grenfell-Shaw and Tester, 2021). This superfood is high in protein, amino acids, vital minerals, and omega-3 fatty acids (Lefton, 2024; Zafar *et al*., 2024).

Weed interference affects crop yield and the levels of essential plant secondary metabolites (Olivoto *et* al., 2016). Knezevic *et al.* (2002) stated that the time frame required for maintaining an area free of weeds in order to avert yield loss is referred to as the critical period of weed control (CPWC). The critical timing of weed removal and the critical weed-free period are the two parts that comprise the CPWC (Contreras *et al.*, 2025). Controlling weeds is crucial at the CPWC stage for the purpose of preventing irreversible yield losses (Safdar *et al.*, 2016). However, it might be difficult to schedule weed management strategies since different invasive plant species must be taken into account (Hossain *et al.*, 2023).

When it comes to choosing, farmers prefer chemicals as they are less labor intensive. Chemicals that are referred to as herbicides are used to suppress or get rid of undesirable plants, commonly referred to as weeds (Cheng and Cheng, 2015). Herbicides function by obstructing particular cellular processes in plants, stunting their growth, or even killing them. According to Al-Khatib (2023), they can stop weeds from growing by interfering with their capacity to photosynthesize or inhibiting growth hormones from being synthesized.

Research on the adverse effects of weeds as well as efficient weed control needs to be conducted, owing to the lack of information on CPWC in quinoa yields, as weed interference can affect yield and secondary metabolites produced by plants (Olivoto *et al.*, 2016). Weed management in quinoa cultivation is challenging due to manual labor, necessitating the development of effective weed control techniques and appropriate herbicide identification, as stated by Taaime *et al.* (2023). Hence, our study aims to determine the CPWC for quinoa cultivation, to evaluate the effects of various weed management practices on growth and yield, and to identify the most suitable herbicide for quinoa cultivation in Bangladesh.

Materials and Methods

The study was conducted between November 2023 and February 2024 at Sher-e-Bangla Agricultural University in Dhaka, Bangladesh, at the Dr. Kazi M. Badruddoza Research Center and the Agronomy research area. The experimental area was located within the Madhupur Tract's AEZ 28, specifically in the Tejgaon soil series. The climate of the region was subtropical, with temperatures ranging from 6 to 9 °C in January to maximum of 36 to 44 °C in April and May. The region has a recent average annual rainfall of 1590 mm, with 90% of this falling between May and September. At the experimental site, measurements were taken of the rainfall amount, as well as in the lowest and highest temperatures, during the experimental period (Figure 1). The test soil comprised of 26% sand, 45% silt, and 29% clay, thus the textural class was silty-clay. Further, the soil pH was 5.6 having 0.45% organic carbon, 0.03% N, 20.0 ppm P, 0.10 mg K 100 g^{-1} soil, and 45 ppm S. In addition, the soil of the experimental plots was low (0.78%) in organic matter and slightly acidic in reaction. Quinoa var. SAU Quinoa-1 was used in the studies as an experimental crop.

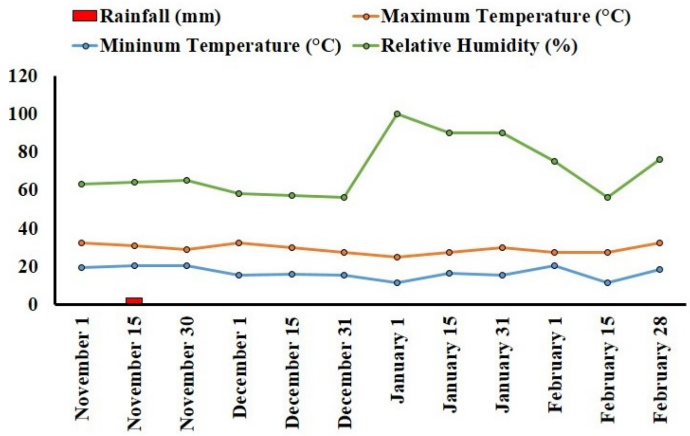

Figure 1: *Meteorological observations from November 2023 to February 2024*

Germination study

A germination study on quinoa was conducted to evaluate the effectiveness of the pre-emergence herbicide, pendimethalin 33% EC, at five different dosages: 1/8X, 1/4X, 1/2X, X, and 2X. In this context, X represents the recommended dose of 2000 mL ha^{-1} in 500 L of water.

In another study, a mixed herbicide (mesotrione 2.27% + atrazine 22.7% SC) was applied on germinating seedlings (four days after seed placement) at five different doses: 1/8X, 1/4X, 1/2X, X, and 2X, where X represents the recommended dose of 3000 mL ha^{-1} in 1000 L of water. In both cases, the control treatment was treated with distilled water (CK). The inhibition rate of plant height (%) compared to the control group was then recorded using the following formula (Seefeldt *et al.*, 1995):

$$\text{Inhibition (\%)} = \left(\frac{\text{Control plant height} - \text{Plant height treated with herbicide}}{\text{Control plant height}}\right) \times 100$$

In both studies, quinoa seeds were placed onto moistened filter papers in Petri dishes (4.5cm in diameter), germinating in a growth chamber under a 12/12 h dark/light period. Each Petri dish area was converted to a hectare for spraying herbicidal treatment.

Whole-plant herbicide assay

In the pot experiment, quinoa was grown in plastic pots (15 cm in diameter) filled with potting mix, to identify the possible effects of different doses of post-emergence herbicide (sodium acifluorfen 16.5% + clodinafop propargyl 8% EC) at five different doses: 1/8X, 1/4X, 1/2X, X, and 2X, where X represents the recommended dose of 988 mL ha^{-1} in 500 L of water. Each pot area was converted to a hectare for spraying herbicidal treatment. The effect of herbicides on quinoa seedlings was rated visually at two weeks after treatment and was assessed on an S, r, and R scale, where S = death or necrosis of all plant tissues; r = visible symptoms with a possible reduction in biomass; R = very mild symptoms or no visible injury.

Field study

In the field study, the weed removal treatments comprised three components: weed-free periods, weed competition periods, and chemical weeding. The weed-free plots were hand weeded for 0-56 days after sowing. The doses of herbicide were selected for the field trial based on the previous germination and whole plant bioassay experiments. Thus, the experiment comprised 12 treatments with three replications *viz.* T_0: weedy from sowing to harvest (control), T_1: weed-free up to 2 weeks, T_2: weed-free until 4 weeks, T_3: weed-free until 6 weeks, T_4: weed-free until 8 weeks, T_5: weed-free up to harvest, T_6: weedy until 7 weeks, T_7: weedy until 9 weeks, T_8: pre-emergence herbicide (pendimethalin 33% EC at the rate of 2000 mL ha^{-1}), T_9: Post-emergence herbicide (sodium acifluorfen 16.5% + clodinafop propargyl 8% EC at the rate of 988 mL ha^{-1}) at 20 DAS, T_{10}: pre-emergence herbicide with sequentially post-emergence herbicide, and T_{11}: Mixed (pre- and post-emergence) herbicide (mesotrione 2.27% + atrazine 22.7% SC at the rate of 3000 mL ha^{-1}) at 4 DAS. Weeding was performed with hand hoes following the requirements of treatments. The research treatments were applied to 36 uniform-sized plots (5 m^2) within a randomized complete block design (RCBD). Data on weed indices, crop growth, SPAD values, yield parameters, and overall yield were recorded. The SPAD-502 Plus chlorophyll meter (KONICA MINOLTA, Japan) was used to measure leaf chlorophyll content by dual-wavelength absorbance at 650 nm and 940 nm. It has a measurement spot size of 2 × 3 mm and provides repeatability of ±1 SPAD unit, with three readings averaged for each leaf observation.

Determining the weed interference matrices

Two sets of yield data from field experiments assessed the effects of weed interference and weed-free durations on quinoa yield. For weed interference treatments, weeds were allowed to grow for 0, 49, or 63 days after sowing before a weed-free period until harvest. In weed-free treatments, weeds were removed for 14, 28, 42, or 56 days after sowing before allowing growth until harvest. Grain yield was measured at maturity for each treatment. The critical time for weed removal (CTWR) and the critical weed-free period (CWFP) were estimated using a logistic model and threshold-based approach. The fitting of the logistic curve to reach a 95% relative yield loss threshold was achieved through algebraic inversion of the logistic equation. In CTWR analysis, the full-season weedy treatment (T_0) equated to 0 days of weed-free period, with treatments weedy until 7 weeks (T_6) and 9 weeks (T_7) representing 49 DAS and 63 DAS of weed interference, respectively, following the standard CPWC analytical framework described by Knezevic *et al.* (2002).

The statistical analysis of variance (ANOVA) was used to examine data on all necessary parameters, including germination percentage, weed dry weight, SPAD value, 1000-seed weight, seed yield, and biological yield, using a computer application called Statistix 10. The LSD test used to adjust the mean differences (p≤0.05). The non-linear least squares (NLS) in Python using scipy.optimize.curve_fit was used to fit the logistic model with biologically relevant parameter constraints.

Results and Discussion

Germination bioassay

The rate of quinoa seed germination significantly declined with increasing concentration of herbicide (Figure 2). Seven days after seed imbibition, the application of five doses of pendimethalin 33% EC had a substantial effect on the germination rate of the quinoa seeds. While the average germination rate for quinoa seeds treated with pendimethalin 33% EC at twice the recommended dose (2000 mL ha^{-1} in 500 L of water) was found to be below 40%, the average germination rate for seeds treated with other dose treatments was not significantly different from the control group, with all treatments having an average germination rate above 93%. The results indicate low adverse effect of pendamethalin on germination of quinoa and show herbicide tolerance under 1/8X, 1/4X, 1/2X and recommended dose (Darabkhani *et al*., 2024). The findings supported previous research, showing that quinoa has a certain degree of herbicide tolerance and the capacity to regain growth in areas where higher dose herbicide reduce growth of quinoa (Xiong *et al*., 2024). According to McGinty *et al.* (2023), thick seed coat induced dormancy prevent the germination under herbicide stress.

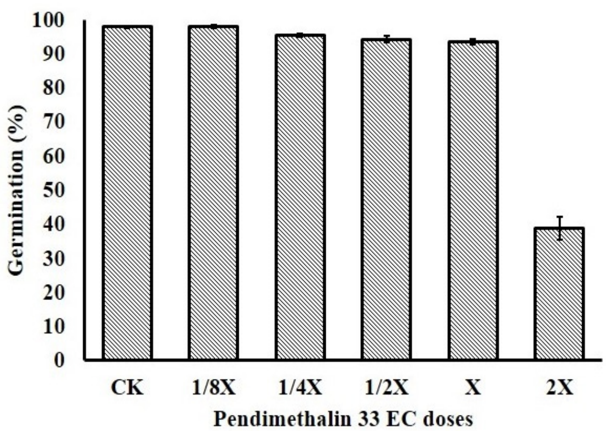

Figure 2: *Effect of pendimethalin 33% EC doses on the germination percentage of quinoa seed*

As shown in Figure 2, the growth of quinoa was considerably affected with two times the concentration of the recommended amount (3000 mL ha^{-1} in 1000 L of water) of mixed pre-and post-emergence herbicide (mesotrione 2.27% + atrazine 22.7% SC) where the plant height inhibition rate was 82.42%. Just 7 days after the application, quinoa showed high-level phytotoxicity symptoms as the apex failing to unfurl with stem deformity and shriveling. In the case of the other applications, by 14 days after herbicide application, all the quinoa plants were died. In contrast, the lower concentrations of the mixed pre-and post-emergence herbicide including the recommended dose had low inhibition on quinoa (1.47% to 5.70%). Although the degree of inhibition increased with increasing the concentration by 1/8, 1/4, and 1/2 times of the recommended dose of mesotrione 2.27% + atrazine 22.7% SC, but data not showed statistically significant. The results suggesting that the recommended dose of the mixed herbicide applied to the field conditions it did not reduce germination or negatively affect on the initial growth of the quinoa seedlings. It was revealed that although both pre- and post-emergence mixed herbicide suppressed weed populations, herbicide with mixed forms of pre- and post-emergence would apply some growth pressure on the crop itself (Xiong *et al*., 2024).

Table 1: *Effect of sodium acifluorfen 16.5% + clodinafop propargyl 8% EC doses on the seedlings of quinoa*

Doses	SCALE			
	S	r	R	Remarks
1/8X			✓	
1/4X			✓	
1/2X			✓	
X		✓	✓	Both observed
2X	✓			

Where X represents the recommended dose of 988 mL ha^{-1} in 500 L of water; S = death or necrosis of all plant tissues; r = visible symptoms with a possible reduction in biomass; R = very mild symptoms or no visible injury

Whole-plant herbicide assay

During the whole-plant evaluation, the leaves and stems were each assessed separately for herbicide damage. The petioles and branches were combined with the main stem and evaluated together as stem damage, while the leaves were assessed individually as leaf damage. Symptoms or injury observed on leaves were scored using the scale outlined in Table 1. Among five doses of post-emergence herbicide (sodium acifluorfen 16.5% + clodinafop propargyl 8% EC), those that were double the recommended rate (988 mL ha^{-1} in 500 L of water) showed the most severe necrosis in quinoa. While lower rates caused very mild symptoms or no visible injury, the recommended label dose resulted in visible symptoms and possibly reduced biomass. This may have occurred due to adjustments in the ratios of the components or exploring other combinations that could be effective at lower rates. Darabkhani *et al.* (2024) also found that quinoa had the sensitivity of high doses of post-emergence herbicides. Ultimately, the recommended rate for sodium acifluorfen 16.5% + clodinafop propargyl 8% EC for the field trial was selected.

Field study

Weed dynamics

Fourteen different weed species from nine different families were found in the experimental field. The grasses and broad-leaf weeds dominated the entire experimental site the most. The weeds were grasses, i.e., *Cynodon dactylon*, and *Eleusine indica*, sedges, i.e., *Cyperus rotundus*, and *C. esculentus*, and broad-leaf, i.e., *Alternanthera philoxeroides*, *Amaranthus viridis*, *Solanum carolinense*, *Physalis heterophylla*, *Heliotropium indicum*, *Rorippa indica*, *Polygonum flaccidum*, *Corchorus trilocularis*, *Gnaphalium luteo-album*, *Mimosa pudica*, belonging to Poaceae, Cyperaceae, Amaranthaceae, Solanaceae, Boraginaceae, Brassicaceae, Polygonaceae, Malvaceae, and Fabaceae, respectively. Similar weed assemblages, particularly dominated by *C. dactylon*, and *C. rotundus*, have been reported in cereal-based cropping systems of Bangladesh (Islam *et al*., 2017; Hossain *et al*., 2023)

Weed density (no. m^{-2}) is a key parameter for evaluating weed control treatment performance. As shown in Table 2, weed density varied significantly across treatments. In control plots, weed counts were highest at 92 and 102 m^{-2} at 30 and 60 DAS, respectively, similar to T_6 (weedy until 7 weeks) and T_7 (weedy until 9 weeks) at 30 DAS, and T_7 at 60 DAS. The lowest weed densities at 30 DAS (0 m^{-2}) were in T_2 (weed-free 2-4 weeks) and T_5 (weed-free till harvest), while at 60 DAS, T_5 had the lowest density, due to manual removal. Sequential herbicide application (T_{10}) most effectively reduced weed density, consistent with earlier reports that integrated herbicide strategies provide superior control in quinoa (Merino *et al*., 2020) and other small-seeded crops. However, in this study, the crop died following post-emergence herbicide at 20 DAS, indicating phytotoxic issues.

The dry biomass of weeds varied significantly across treatments (Table 2). The highest dry weights of 34.94 g and 38.21 g were from weedy plots at 30 and 60 DAS, respectively, and were statistically similar to treatments T_6 (weedy until 7 weeks), T_7 (weedy until 9 weeks) at 30 DAS, and T_7 at 60 DAS. Sequential herbicide application (T_{10}) minimized weed biomass, aligning with findings by Safder *et al*. (2016) in maize and by Islam *et al*. (2017) in rice, who demonstrated that unchecked weed growth drastically increases biomass accumulation and reduces yield.

Crop growth performance

Plant height

The plant height of quinoa varied significantly throughout the growth period due to the different

Table 2: *Effect of different weed management practices on weed density and weed dry weight of quinoa*

Treatments	Weed density (no. m^{-2})		Weed dry weight (g)	
	30 DAS	60 DAS	30 DAS	**60 DAS**
T_0	92.33 ± 3.18 a	101.67 ± 3.48 a	34.94 ± 3.79 a	38.21 ± 1.73 a
T_1	22.67 ± 2.19 d	78.33 ± 3.84 b	12.90 ± 1.39 d	29.70 ± 0.82 b
T_2	0.00 ± 0.00 f	30.33 ± 0.88 e	0.00 ± 0.00 f	18.57 ± 1.14 d
T_3	75.67 ± 1.76 b	14.00 ± 2.08 gh	22.12 ± 0.83 b	13.51 ± 1.36 e
T_4	77.33 ± 1.76 b	0.00 ± 0.00 i	20.00 ± 0.62 bc	0.00 ± 0.00 g
T_5	0.00 ± 0.00 f	0.00 ± 0.00 i	0.00 ± 0.00 f	0.00 ± 0.00 g
T_6	90.67 ± 4.91 a	8.67 ± 0.88 h	33.82 ± 3.45 a	7.43 ± 0.49 f
T_7	91.33 ± 1.45 a	96.00 ± 2.52 a	34.14 ± 2.97 a	37.97 ± 0.69 a
T_8	35.00 ± 2.65 c	62.00 ± 1.73 c	19.58 ± 1.25 bc	26.45 ± 0.84 bc
T_9	10.33 ± 1.20 e	21.33 ± 1.45 f	7.97 ± 1.48 e	18.70 ± 4.23 d
T_{10}	5.00 ± 2.08 ef	15.33 ± 3.71 fg	1.04 ± 0.39 f	11.51 ± 1.46 ef
T_{11}	32.67 ± 2.03 c	55.33 ± 1.45 d	16.94 ± 0.42 cd	23.11 ± 0.90 c
$LSD_{0.05}$	6.23	6.13	4.70	4.16
CV (%)	8.29	8.99	16.37	13.11

In a column means having similar letter(s) are statistically identical and those having dissimilar letter(s) differ significantly at 0.05 level of probability. ± represents SE values for three biological replications. Here, T_0: weedy from sowing to harvest (control), T_1: weed-free up to 2 weeks, T_2: weed-free until 4 weeks, T_3: weed-free until 6 weeks, T_4: weed-free until 8 weeks, T_5: weed-free up to harvest, T_6: weedy until 7 weeks, T_7: weedy until 9 weeks, T_8: pre-emergence herbicide (pendimethalin 33% EC @ 2000 mL ha^{-1}), T_9: Post-emergence herbicide (sodium acifluorfen 16.5% + clodinafop propargyl 8% EC @ 988 mL ha^{-1}), T_{10}: pre-emergence herbicide with sequentially post-emergence herbicide, *and T_{11}: Mixed (pre + post) herbicide (mesotrione 2.27% + atrazine 22.7% SC 3000 mL ha^{-1}).*

weed management treatments (Table 3). The tallest plants (11.11, 23.61, 52.89, and 52.13 cm) were observed in plots treated with pendimethalin, followed by weed-free plants for up to 2 weeks (10.63, 22.35, 50.96, and 50.61 cm) at 15, 30, 45 DAS, and at harvest, respectively. In contrast, the shortest plants were observed in the control plots (8.55, 18.30, 41.17, and 40.73 cm) and weedy until 9 weeks (8.23, 18.27, 42.07, and 41.25 cm) at 15, 30, 45 DAS, and at harvest accordingly, which were statistically similar with several treatments. Xiong *et al.* (2024) supported the result and stated that pre-emergence herbicides exhibited weaker inhibitory effects on quinoa plant height and root length.

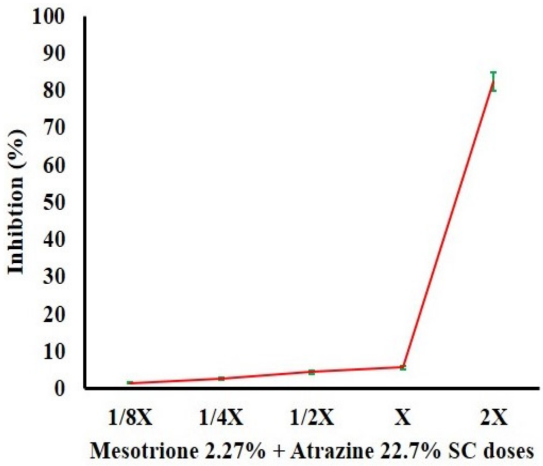

Figure 3: *Effect of mesotrione 2.27% + atrazine 22.7% SC doses on the inhibition percentage of plant height of quinoa seed*

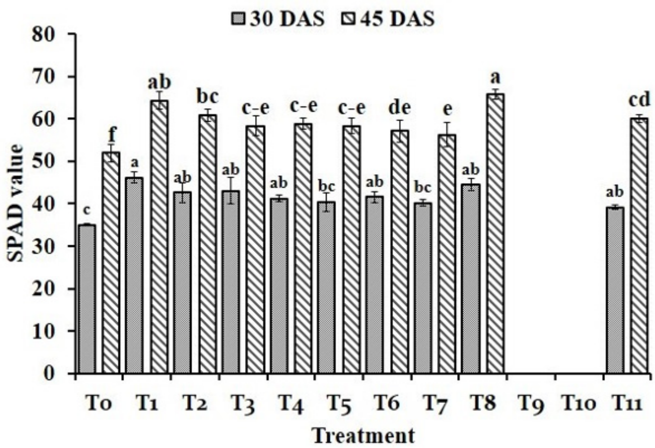

Figure 4: *Effect of different weed management practices on chlorophyll content (SPAD value)*

SPAD value

The chlorophyll content of leaves varied significantly throughout the growth period due to weed management (Figure 4). The highest SPAD value (46.17) at 30 DAS was observed in the weed-free plants for up to 2 weeks (T_1). However, at 45 DAS, the highest SPAD value of 65.69 was observed in the plants that received pendimethalin. In contrast, the lowest SPAD value was observed from the weedy control plots, which were 35.04 and 51.91 at 30 and 45 DAS, respectively. According to Santos *et al.* (2003), Imazaquin was the most harmful to quinoa seedlings, while trifluralin and pendimethalin had no residual effect. Moreover, Merino *et al.* (2020) found that the herbicide rate slightly affected foliar injury in quinoa crops; the injury symptoms decreased as more days passed.

Table 3: *Effect of different weed management practices on plant height of quinoa*

Treat-ments	Plant height (cm)			
	15 DAS	30 DAS	45 DAS	At harvest
T_0	8.55 ± 0.42 d	18.30 ± 0.48 e	41.17 ± 1.51 c	40.73 ± 1.43c
T_1	10.63 ± 0.04 a-c	22.35 ± 1.56 ab	50.96 ± 2.13 ab	50.61 ± 2.07 ab
T_2	9.43 ± 0.56 b-d	21.75 ± 1.11 a-c	48.71 ± 3.41 a-c	47.73 ± 3.32 a-c
T_3	8.93 ± 1.17 d	21.22 ± 1.32 a-d	48.33 ± 0.77 a-c	47.96 ± 0.79 a-c
T_4	8.39 ± 0.36 d	19.88 ± 0.98 b-e	44.73 ± 2.89 a-c	44.10 ± 2.83 bc
T_5	8.38 ± 1.02 d	18.76 ± 1.12 de	42.53 ± 3.13 c	41.35 ± 3.03 c
T_6	9.22 ± 0.60 cd	19.74 ± 1.07 b-e	43.45 ± 4.80 bc	42.57 ± 4.59 c
T_7	8.23 ± 0.36 d	18.27 ± 1.16 e	42.07 ± 2.05 c	41.25 ± 2.17 c
T_8	11.11 ± 0.27 a	23.61 ± 2.12 a	52.89 ± 4.91 a	52.13 ± 4.80 a
T_9	8.04 ± 0.30 d	-	-	-
T_{10}	10.95 ± 0.27 ab	-	-	-
T_{11}	8.30 ± 0.23 d	19.38 ± 0.74 c-e	43.71 ± 1.41 bc	42.98 ± 1.14 bc
$LSD_{0.05}$	1.52	2.77	8.27	8.03
CV (%)	11.84	7.93	10.52	10.37

In a column means having identical letter(s) are statistically similar and those having dissimilar letter(s) differ significantly at 0.05 level of probability. ± represents SE values for three biological replications. Here, T_0: weedy from sowing to harvest (control), T_1: weed-free up to 2 weeks, T_2: weed-free until 4 weeks, T_3: weed-free until 6 weeks, T_4: weed-free until 8 weeks, T_5: weed-free up to harvest, T_6: weedy until 7 weeks, T_7: weedy until 9 weeks, T_8: pre-emergence herbicide (pendimethalin 33% EC @ 2000 mL ha^{-1}), T_9: Post-emergence herbicide (sodium acifluorfen 16.5% + clodinafop propargyl 8% EC @ 988 mL ha^{-1}), T_{10}: pre-emergence herbicide with sequentially post-emergence herbicide, and T_{11}: Mixed (pre + post) herbicide *(mesotrione 2.27% + atrazine 22.7% SC 3000 mL ha^{-1}). (-) denotes not included as all plants died.*

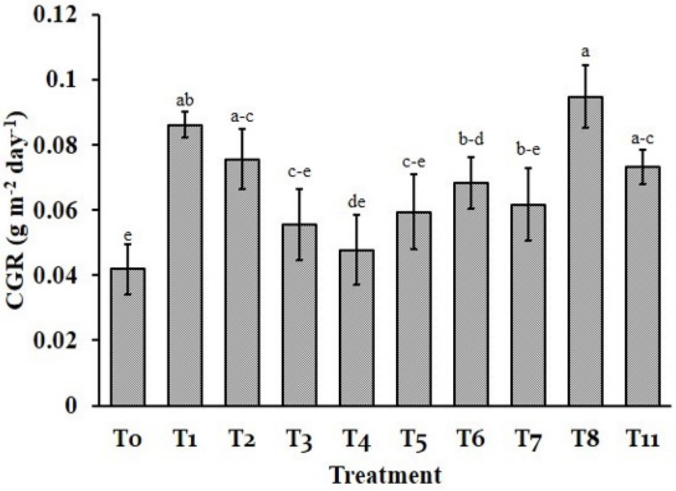

Figure 5: *Effect of different weed management on crop growth rate of quinoa ($LSD_{0.05}$ = 0.02; CV% = 21.65)*

Table 4: *Effect of different weed management on the yield contributing parameters of quinoa*

Treat-ments	No. of effective branches plant^{-1}	No. of inflores-cences plant^{-1}	1000-seed weight (g)
T_0	11.67 ± 0.33 f	13.33 ± 0.33 g	1.96 ± 0.06 g
T_1	19.13 ± 0.47 a	19.87 ± 0.55 a	3.49 ± 0.07 a
T_2	18.13 ± 0.13 ab	18.60 ± 0.31 bc	2.97 ± 0.03 b
T_3	17.93 ± 0.07 bc	18.40 ± 0.40 cd	2.89 ± 0.06 bc
T_4	17.07 ± 0.07 b-d	17.20 ± 0.12 e	2.78 ± 0.06 cd
T_5	16.67 ± 0.33 d	17.20 ± 0.12 e	2.64 ± 0.05 de
T_6	14.60 ± 0.50 e	15.00 ± 0.42 f	2.26 ± 0.14 f
T_7	12.33 ± 0.18 f	13.53 ± 0.13 g	2.02 ± 0.07 g
T_8	19.13 ± 0.70 a	19.60 ± 0.42 ab	3.01 ± 0.01 b
T_9	-	-	-
T_{10}	-	-	-
T_{11}	17.00 ± 0.58 cd	17.40 ± 0.70 de	2.60 ± 0.02 e
$LSD_{0.05}$	1.09	1.01	0.17
CV (%)	3.87	3.47	3.65

In a column means having identical letter(s) are statistically similar and those having dissimilar letter(s) differ significantly at 0.05 level of probability. ± represents SE values for three biological replications. Here, T_0: weedy from sowing to harvest (control), T_1: weed-free up to 2 weeks, T_2: weed-free until 4 weeks, T_3: weed-free until 6 weeks, T_4: weed-free until 8 weeks, T_5: weed-free up to harvest, T_6: weedy until 7 weeks, T_7: weedy until 9 weeks, T_8: pre-emergence herbicide (pendimethalin 33% EC @ 2000 mL ha^{-1}), T_9: Post-emergent herbicide (sodium acifluorfen 16.5% + clodinafop propargyl 8% EC @ 988 mL ha^{-1}), T_{10}: pre-emergence herbicide with sequentially post-emergence herbicide, and T_{11}: Mixed (pre + post) herbicide (mesotrione 2.27% + atrazine 22.7% SC 3000 mL ha^{-1}). (-) denotes not included as all plants died.

Crop growth rate (CGR)

Different weed management practices affected the crop growth rate of quinoa considerably. As demonstrated in Figure 5, it can be observed that pendimethalin-treated plots (T_8) recorded the highest crop growth rate of 0.095 g m^{-2} day^{-1}. The plots where weeding was performed within 2 weeks (T_1) recorded the second highest value of 0.086 g m^{-2} day^{-1}. In contrast, control plots (T_0) recorded the lowest crop growth rate of 0.042 g m^{-2} day^{-1}. The study of Guleria *et al.* (2024) showed that the application of pendimethalin at 1000 mL ha^{-1} resulted in the highest growth parameters, including plant height, dry matter accumulation, and CGR.

Yield contributing traits and yield

No. of effective branches plant^{-1}

The number of effective branches plant^{-1} of quinoa significantly varied due to the different weed management (Table 4). The maximum number of effective branches (19) was found in both treatments, weed-free for up to 2 weeks (T_1) and the application of pendimethalin (T_8), which was not entirely dissimilar to the treatment that was weed-free for 2 to 4 weeks. In contrast, the lowest number of effective branches plant^{-1} was observed in the weedy control (T_0), having a value of 12. The study of Jacobsen *et al.* (2010) examined mechanical weeding strategies like weed harrowing and inter-row hoeing and found that hoeing yielded more due to better weed control.

Number of inflorescences plant^{-1}

The number of inflorescences plant^{-1} of quinoa was noticeably different due to the variations of weed management (Table 4). The maximum number of inflorescences plant^{-1} (20) was found to be weed-free for up to 2 weeks (T_1), followed by the pendimethalin-received plants. In contrast, the lowest number of inflorescences plant^{-1} was found in weedy check plots (13), which were statistically similar to those that were weedy until 9 weeks (T_7). Tran *et al.* (2025) found that yield components including number of inflorescences plant^{-1} were significantly affected by weed management.

1000-seed weight

Notable variation was observed in the 1000-seed weight (g) of quinoa for different weed management (Table 4). The maximal 1000-seed weight was found for quinoa that was weed-free for up to 2 weeks (T_1), having a value of 3.49 g, and the least weight found for quinoa in weedy control plants (1.96), which was statistically similar to those that were weedy up to 9 weeks (2.02 g). Taaime *et al*. (2023) supported our result and reported that quinoa crops benefit from early weeding (± 30 DAS) to lessen plant competition for scarce nutrients.

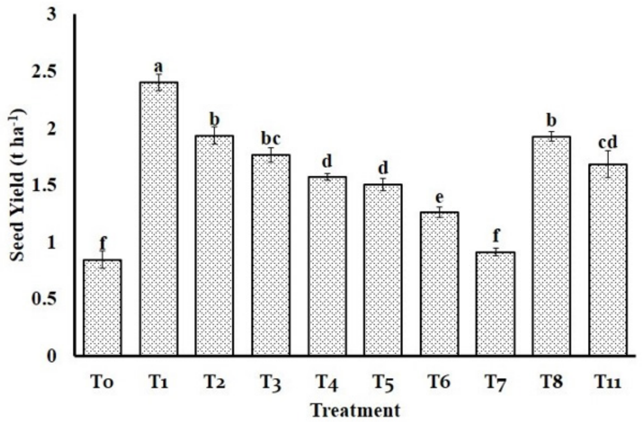

Figure 6: *Effect of different weed management on seed yield of quinoa (LSD$_{0.05}$ = 0.19; CV% = 7.14)*

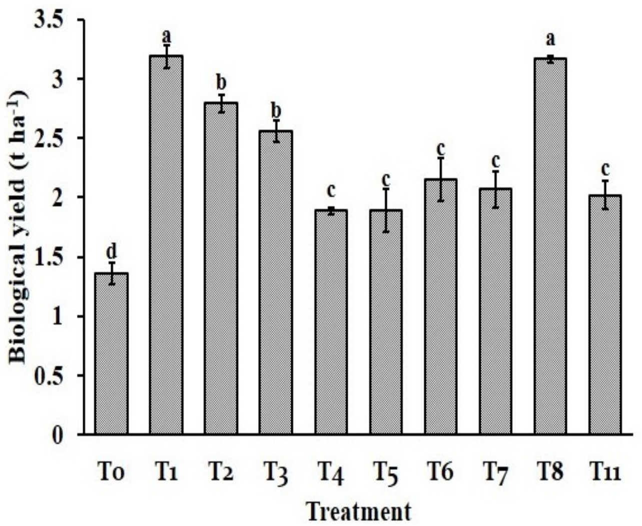

Figure 7: *Effect of different weed management practices on biological yield (LSD$_{0.05}$ = 0.36, CV% = 8.97)*

Seed yield

Different weed management treatments considerably influenced seed yield (Figure 6). The highest seed yield (2.36 t ha^{-1}) of quinoa was recorded in T$_1$ (weed-free up to 2 weeks), followed by the application of pendimethalin (T$_8$), and which was weed-free until 4 weeks (T$_2$). Meanwhile, the lowest seed yield of quinoa was observed in the weedy control treatment, which was approximately 64.58% lower than T$_1$ and statistically similar to that of the weedy treatment until 9 weeks (T$_7$). In a study on chemical weed control in quinoa, Molina *et al*. (2014) conducted a chemical weed control experiment in quinoa, using postemergence herbicides (fomesafen, bentazon, and metsulfuron-methyl) along with manual weed control, as well as no weed control, as two control treatments. They showed the highest yield in manual weed control, not significantly different from three fomesafen applications, and the lowest with one metsulfuron-methyl application.

Biological yield

Different weed management practices differed in the biological yield (t ha^{-1}) of quinoa. From Figure 7, it can be perceived that the plots where weeding was performed within 2 weeks (T$_1$) recorded the maximal biological yield of 3.19 t ha$^{-1,}$ and it was statistically similar to pendimethalin-treated plots (T$_8$). In contrast, control plots (T$_0$) recorded the lowest biological yield of 1.36 t ha^{-1}. The study of Dheeraj *et al*. (2023) showed that plots with early hand weeding produced higher biological yield, which supports our findings.

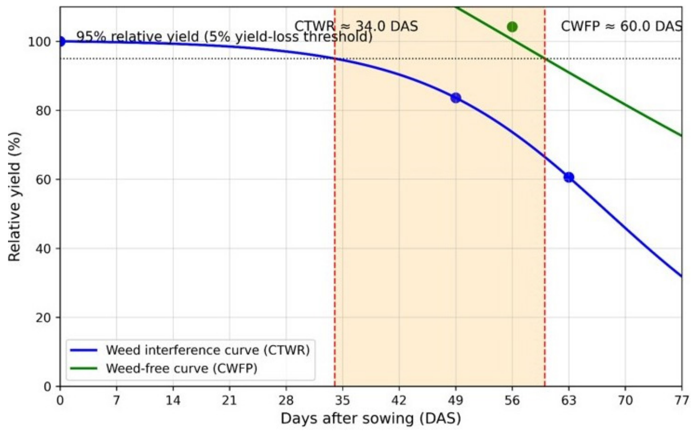

Figure 8: *Determination of the critical period for the weed competition in quinoa*

Determination of the critical period for the weed competition

The critical period of weed competition was calculated from two data sets i.e., one representing yield decline with increasing weed interference and the other representing yield recovery with increasing weed-free duration, following the analytical framework of Knezevic *et al*. (2002). In this research, the typical second dataset (lowest to highest) was not obtained because increasing the weed-free period through manual weeding decreased yields. This trend suggests that repeated manual weeding may cause stress through factors such as soil moisture loss, root disturbance from repeated weeding, and changes in microclimate. Consequently, the graphical analysis proceeded by fitting logistic models to both datasets and generating smooth prediction curves (0–77 DAS) for estimating the critical time for weed removal (CTWR) and critical weed-free period (CWFP). Visualization included logistic curves, observed data points, a 95% yield-loss threshold, vertical lines indicating CTWR and CWFP, and a shaded region representing the CPWC (Figure 8).

The yield of quinoa decreases with prolonged weed interference. Yield was reduced by approximately 16% at 49 DAS and by nearly 40% at 63 DAS. This trend shows quinoa is especially vulnerable to early-season weed pressure, which can permanently reduce its production potential. Langeroodi *et al.* (2020) indicated that the slow development rate, particularly after crop emergence, is most noticeable in quinoa. Therefore, the logistic model applied to the weed interference dataset clearly showed that relative yield decreases as weed interference duration increases with the CTWR is identified as 34 DAS for a 5% acceptable yield loss. This indicates that weeds emerging during the first five weeks after sowing cause irreversible yield losses if not removed.

Quinoa yield in this study showed a unique response to extended weed-free periods, decreasing as the weed-free duration increased beyond 14 DAS, after which yields declined progressively at 28, 42, and 56 DAS. The logistic model fitted to these data confirmed the declining yield trend and identified the CWFP threshold at 60 DAS, the duration required to prevent more than 5% yield loss. The combine response indicated that quinoa yield was most vulnerable to weeds between 34 and 60 DAS, identifying the CPWC. Maintaining weed-free conditions during this period is crucial to prevent significant yield and economic loss. Merino *et al.* (2019) stated that there is limited information on the critical period of weed interference in quinoa. However, they also found that the crop must be weed-free from the two true leaf stage until flowering to avoid production losses exceeding 5%.

Conclusions and Recommendations

The study on the critical weeding period and the effect of herbicide doses on the growth and yield of quinoa has provided valuable insights into optimizing quinoa production under varying weed management strategies. The results demonstrated that quinoa exhibited a relatively sensitive response to both the timing of weed removal and the application of herbicides, with clear implications for maximizing yield. The critical weed-free period for quinoa was found to occur within 34 to 60 DAS. During this period, quinoa plants were most susceptible to competition from weeds, which could significantly reduce the plant growth and yield. Delaying weeding beyond this critical window lead to significant yield losses due to intensified weed competition for water, nutrients, and light. The study also revealed that the herbicide pendimethalin application, when applied at a 2000 mL ha^{-1} dose, could effectively control weed pressure without detrimental effects on quinoa growth. These findings accentuate the importance of timely weed management and judicious herbicide use in maintaining high quinoa productivity. Moreover, the findings offer practical guidance for farmers seeking to increase yields while minimizing both the economic costs and environmental impacts of weed control.

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Novelty Statement

This study quantitatively identifies the critical period of weed control (CPWC) in quinoa using yield-loss modeling while assessing the effectiveness of pre- and post-emergence herbicides. The findings provide a new framework for optimizing herbicide timing and enhancing quinoa productivity in emerging cultivation areas.

Author's Contribution

Most. Nasrin Bari Neela: Performed the research experiment, formal analysis and wrote the manuscript.
Tanvir Ahmad Sourav: Performed the research experiment, formal analysis and wrote the manuscript
Md. Hasanuzzaman: Conducted the literature review
Sheikh Muhammad Masum: Developed the research plan, supervised the research, manuscript review.

Generative AI or AI assisted technology statement
The authors declare that no generative AI or AI-assisted technologies were used in the writing, analysis, or preparation of this manuscript.

Conflict of interest

The authors have no conflict of interest.

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